[Salcedo, R., Granell, R., Palau, G., Vallet, A., Garcera, C., Chueca, P., Molto, E. (2015). Design and validation of a 2D CFD model of the airflow produced by an airblast sprayer during pesticide treatments of citrus. Computers and Electronics in Agriculture, 116, 150-161.]

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DESIGN AND VALIDATION OF A 2D CFD MODEL OF THE AIRFLOW PRODUCED BY AN AIRBLAST SPRAYER DURING PESTICIDE TREATMENTS OF CITRUS

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Abstract

During plant protection treatments using air blast sprayers, part of the chemical is lost in the atmosphere (spray drift), ground, surface water, etc., causing risks to the environment. Although there is a growing interest in quantifying these losses, field measurements are extraordinarily complex and expensive. Computational Fluid Dynamics (CFD) generates mathematical models of this phenomenon that may help to understand and quantify it. The air flow produced by the fan is affected by the canopies, which modify the trajectories of spray droplets. Current state of the art in CFD consider canopies as porous bodies and use the k-ε turbulence model. In a first step, this work proposes and validates a two dimensional CFD model to be applied in citrus tree applications from experimental data. This new CFD model considers canopies as solid bodies. Four different geometries for the first tree are compared using three different turbulence models: k-ε, SST k-ω and Reynolds Stress Model. Air velocities measured in front of a canopy in a previous field test are introduced as boundary conditions. We used the experimental data to adjust the model and select the geometry and the turbulence model. In order to test the validity of the model, air velocities obtained with

the model are compared with the experimental data obtained in other experiment. The final CFD model was able to reproduce the airflow behavior around the canopy, with the same turbulent structures. The solid body with the new turbulence model (SST k-ω) was considered as a good approximation to the real life.

Research highlights

- Specific turbulent structures on airflow in plant protection treatments with air blast sprayer in orange trees have been observed.
- In a first step, a new 2D CFD model considering the canopy as a solid body with a new turbulent air model was proposed to study the phenomenon.
- CFD model was adjusted and validated with different experimental data, reproducing the same turbulent structures.

Keywords: fan, spray drift, simulation, Navier-Stokes equations, RANS models

1. Introduction

Pesticide treatments in citrus are normally applied with airblast sprayers. Droplets produced by these equipments are transported by an airflow generated by a fan, which helps them penetrate tree canopies and spread over vegetation.

During the application of plant protection products only a fraction of the spray reaches the vegetation. A portion of the spray falls to the ground or quickly evaporate and another is dispersed into the atmosphere, leaving the area being treated, what is called spray drift (ISO, 2005). Such losses may contaminate the environment (air, ground, water, other crops, buildings, etc.) affecting fauna, flora, residents and by-standers.

Mass balance of pesticide treatments primarily depends on the vegetation (Praat *et al*., 2000), equipment design (Holownicki *et al.*, 2000), operational parameters (Bouse, 1994), spray mix properties (De Schampheliere *et al*., 2009), and weather conditions (Nuyttens *et al.*, 2005).

European legislation (EU, 2009) established that the impact of pesticide use on human health and environment should be assessed. The first step to achieve this objective is to quantify the amount of spray volume that reaches each substrate (vegetation, ground and atmosphere).

Several methods have been used to quantify off-target losses, deposition or mass balance of the spray applications in field conditions (Balsari *et al.*, 2005; ISO, 2005; Gil *et al.*, 2007; Salyani *et al.*, 2007). However, these trials are very expensive and time-consuming. As they consist in experiments performed outdoors, it is very difficult to control all the factors that influence spray distribution, and they are also almost impossible to be reproduced.

The use of physico-mathematical models to describe drift, deposition or spray distribution can be a good alternative for or may supplement field trials (Walklate, 1987, 1992; Hewitt *et al*., 2002; Larbi and Salyani, 2011). Such models may simulate the influence of certain factors on mass balance, which is not often easy to appreciate in field experiments (Gil and Sinfort, 2005). They have proved to be useful to describe spray distribution and have become increasingly accurate over the years.

One type of models is based on computational fluid dynamics (CFD), where numerical methods are employed to solve the Navier-Stokes equations, which govern the turbulent performance of fluids (Versteeg and Malalasekera, 1995). Reynolds Average Navier-Stokes (RANS) models are the most widely used in engineering because they offer acceptable solutions at a reasonable computational cost. Flow equations in RANS models are simplified by averaging velocity and pressure. However, new unknown variables are added to the flow equations. A series of turbulence models is used to complete the number of equations to solve the system. The most widespread turbulence model is the so-called standard k-ε (Launder and Sharma, 1974), which has been employed in several works on spray application with air blast sprayers (Xu *et al*, 1998; Da Silva *et al*, 2006; Endalew *et al*, 2009, 2010ab, 2011; Duga *et al*, 2013).

Some researchers have opted to use alternative models, such as the k-ω model (Wilcox, 1988) as Shelton and Neuman (2011) did, or its variant Shear Stress Transport (SST) (Menter, 1993), like Connell *et al*. (2011). These models are recommended for simulating adverse pressure gradients (Pope, 2000). In general terms, they have good performance for simulating fluid separation and vortexes due to obstacles in the flow. However, they require more computational resources. The so-called Reynold Stress Model (RSM) turbulence models (Launder *et al*., 1975) include equations for all Reynolds stresses and one more equation for turbulence kinetic energy dissipation. They adapt very well to anisotropic flows, but the computational cost involved is even higher.

Vegetation significantly alters the airflow from the fan during the applications. Variations in the airflow modify the trajectories of the sprayed droplets and, therefore, strongly influence mass balance. This is especially important in citrus orchards, since densest tree canopies strongly withstand air movement and produce turbulences inside them and in their surroundings (Finnigan, 2000; Belcher *et al*., 2003; Yi, 2008; Yue *et al*., 2008).

Usually, tree canopy is modelled as a homogeneous and/or porous medium in many CFD studies (Xu *et al*., 1998; Da Silva *et al*., 2006; Shelton and Neuman, 2011). It is considered a homogeneous body that offers certain resistance to the air passing through them. Another approach is to model trunk and branches as a solid medium and the vegetation as a porous medium (Endalew *et al*., 2009, 2010ab, 2011; Duga *et al*., 2013; Connell *et al*., 2013).

Experimental study of airflow produced by an airblast sprayer during pesticide application to citrus showed that two air vortices are generated close to the canopies, one behind the tree and another above it (Salcedo *et al*., 2013, 2015). Previous simulations considering vegetation as an homogeneous porous medium and using the standard k-ε flow model did not show these vortices (Salcedo *et al*., 2012).

Presences of vortices are observed in CFD studies on edification, where buildings are considered as solid bodies (Oke, 1988). When airflow reaches a solid body, air kinetic energy is lost and potential energy increases, which increases air pressure and generates a pressure gradient that the airflow cannot withstand. The pressure gradient alters the direction of the airflow and separates flow on the limiting layer of the solid. A possible new approach to simulate the airflow behaviour observed experimentally is to consider citrus tree as a solid medium. Nonetheless, the characteristics of the solid body could influence the size, intensity and location of these vortices, so it is necessary to conduct a study to determine the shape and size of this body in order to fit the simulation and the experimental data. Likewise, as turbulence models may have an important influence in the results of the simulations, different turbulence models should be compared to select the model that better explains the experimental flow.

The objective of this work is to develop a two-dimensional CFD RANS model as a first step to reproduce the airflow described experimentally and to validate it.

2. Material and Methods

The study to achieve the model was performed using the following steps:

- First trial to obtain experimental data to adjust the model.
- Definition of the general domain and characteristics of the model.
- Simulations to select cell size of the mesh.
- Simulations to select the geometry of the canopy and the turbulence air model.
- Validation of the model with experimental data from a second trial.

2.1 First trial to adjust the model

2.1.1 Air velocity measurement in field conditions

A first trial was conducted in a commercial orchard of ‘Lane Late’ orange trees (*Citrus sinensis* L.). Mean orange tree height was 2.6 m with an approximate diameter of 3.8 m. The distance between parallel rows of trees was 6 m from trunk to trunk.

A conventional airblast sprayer (Pulverizadores Fede S.L., model FUTUR 1500, Cheste, Spain) with an axial fan (diameter 0.9 m) was used to generate the airflow, working at

480 rpm in the PTO and the fan gear that produced the highest air speed. The average air flow was estimated to be 24.4 m^3/s. This figure was calculated by multiplying the average air speed (m/s), measured at different points of the air outlet, and the surface of the air outlet (m^2). The fan was positioned perpendicularly to the rows of trees. The distance between the outer part of the canopy and the fan was 1.05 m. The fan was positioned facing the tree trunk.

This trial consisted in measuring air velocity (magnitude and direction) at different points around the machine and the tree (Figure 1) with a 3D ultrasound anemometer (WindMaster 1590-PK-020, Gill Instruments Ltd., Hampshire, UK). Acquisition time was 60 s at each measuring point, with sampling frequency of 1 Hz. The anemometer provided the three coordinates of the air velocity vector at each point.

On posts A and B, the conditions of the air at the fan outlet were measured. In positions of posts C and D, air velocity was recorded before and after it passed through the tree respectively, similarly to that described in the trial by Da Silva *et al.* (2006). Air velocity was also measured above the canopy (posts E, F and G).

Posts A and B were placed 0.5 m from the fan. Measurements were taken on post A from 0.4 m above the ground, every 0.2 m, to a height of 1.8 m. On post B, air was measured every 0.2 m from the point nearest to post A to the centre of the fan.

Post C stood 0.3 m in front of the tree and post D stood 0.3 m behind the tree. Air was measured on each post every 0.2 m up to a height of 3.0 m.

Posts in positions E, F and G were not set in the ground. Position F represented what happened approximately above the centre of the canopy, while positions E and G were halfway between F and the canopy edges. Since placing posts inside vegetation was difficult because there were many branches and leaves, we estimated an error of ±0.2 m in the positions of the measuring points. Measurements were taken at 0.5 m and 1 m above the top edge of the canopy.

Phytosanitary treatments in Spain should follow standardized good agricultural practices. This implies wind speed lower than 3 m/s during the application (BOE, 2012). We have been much more restrictive than this in our work, in order to avoid the influence of external wind. Wind speed at 5 m height was lower than 1.5 m/s during all recordings in all experiments and for this reason we can considered that its effect is negligible. Furthermore, this assumption of no wind effect has been proposed by other authors. For instance, Zhu et al., 2004 assume that wind profiles close to the canopy surface follow a classical logarithm law. Moreover, Endalew et al. (2009) assumed that the effect of wind is only significant above 1.5 times the height of the trees.

Weather conditions (Temperature, relative humidity and wind velocity) were measured during the experiments, with an ultrasound 2D anemometer (WindSonic, Gill Instruments Ltd., Hampshire, UK) and a thermohygrometer (Log32 Data logger, Dostmann Electronic GMBH, Wertheim - Reicholzheim, Germany), placed 10 m from the machine at a height of 5.0 m. The sensors were located close to the orchard, without obstacles between it and the experiments and avoiding any kind of mutual interference. Sampling frequency was 1 Hz. Weather conditions during the experiments were: average air temperature 23.5 ºC; average relative humidity 43.6%; average wind speed 0.9 m/s (all the values were below 1.4 m/s); and average wind direction 135º (from South-East) respect to the tree row (North-South).

2.1.2 Data analysis and turbulence intensity estimation

The modelled flow was supposed to be stationary. Points that showed stationary air velocity were selected to adjust the model. For this purpose, variations of air velocity at each measuring point were analysed. For this, the average of each air velocity component was calculated every 10 s during 1 min (6 measures). Then, the coefficient of variation of these 6 measures was calculated per each velocity component at each point. Flow was considered to be stable at a given point if the coefficients of variation of all the components of the air velocity were below an arbitrary value of 30%.

Air turbulence intensities are also boundary conditions to be input to the model. In this work, the turbulence intensities at all the A and B post points were calculated. Turbulence intensity (I) at one point was calculated as the ratio of the fluctuations velocities and the mean velocities magnitude:

$$I(\%) = 100\sqrt{u_x'^2 + u_y'^2 + u_z'^2}/\sqrt{U_x^2 + U_y^2 + U_z^2} \quad (1)$$

where u' is the fluctuation at a point in space for a velocity component:

$$u' = u - U \quad (2)$$

where u is the instantaneous velocity at a point (information provided by the anemometer) and U is the mean air velocity value at this point.

2.2 Domain and mesh design

2.2.1 Domain and characteristics

The model was defined in two dimensions as a first step to model the phenomenon. An almost rectangular domain (21 m x 8 m) was considered. A bottom corner was altered to be used as an air inlet, whose shape and size was designed to be similar to those of posts A and B in the trial. Air was allowed to escape through the remaining domain limits, except the base of the rectangle, which represented the ground (Figure 2).

The air inlet was divided into uniform sections of 0.2 m from a height of 0.4 m, and similarly to the way at which measuring points on posts A and B were arranged (Figure 3). Air velocity and turbulence intensity corresponding to the equivalent point of the experiment were assigned to each vertical section. For example, air velocity and turbulence intensity in vertical section A40 corresponded to the measure taken at the measuring point of post A, placed at a height of 0.4 m. The same was done with the horizontal sections, but the post B measurements were used.

2.2.2 Canopy geometries and properties

Inside the domain, three regions corresponding to canopies were defined, each one representing the cross-section of a row of trees. Based on our previous experience (Salcedo *et al*., 2013, 2015), it was decided to consider the region nearest to the air inlet to be a solid medium with homogeneous characteristics, while the other two regions were modelled as a porous medium. Even considering the first region as a solid medium, its dimensions should be smaller than those of the true trees because otherwise the airflow would take a very vertical direction with extremely quick velocities due to the Venturi effect. There must also be enough space between the area representing the canopy and the ground of the domain to sufficiently simulate passing of air that is actually seen in field conditions. Four options were proposed to decide the geometry and size of this region, all of which were symmetrical to a vertical axis (Figure 4). The conditions shared by the four representations of this region were that the distance between the vertical symmetrical axis and the vertical air inlet (the equivalent to post A) was the same as that used in the trial (2.45 m), and that the distance between the vertical symmetrical axes of the three regions representing the canopies was 6.0 m, as in the orchard. The minimum separation between the bottom edge of the region, which represented the first canopy, and the ground was 0.6 m.

Geometries 1 and 2 were different in shape, and had a maximum width of 2.4 m and a maximum height of 1.4 m. Geometry 3 was 2 m wide and 1.2 m high, while Geometry 4 was 2 m wide and 1 m high.

The regions representing the other two rows of trees were simulated as bodies with a porous medium only in the external part (Figure 5) and were placed symmetrically to an horizontal axis and to another vertical one, with a maximum height of 2.6 m (like the trees in the experiment) and a 0.2 metre separation to the ground. The citrus canopies were considered to have a maximum width of 3.8 m in the centre and a minimum width of 3 m at the top and bottom parts, values that were close to the actual average measurements in the field. For this reason, the canopies were modelled using polygonal surfaces that gradually decreased their width from the centre to the top and bottom in a stepped way (Figure 5).

2.2.3 Proposal of different cells size of the meshes for each canopy geometry.

A structured mesh with uniformly distributed quadrilateral cells was used. Since simulation results may depend on the mesh employed (Franke *et al*., 2007), Richardson extrapolation (Shyy *et al*., 2002) was used to determine cell size. For this reason, three meshes were used with a resolution increased by a minimum factor of 1.5 times. Hence for all the geometries of the region representing the first row of trees, cells whose sides measured 20, 10 and 4 cm were employed. Table 1 indicates the number of mesh cells per geometry of the region representing the first canopy.

The determinant 3x3x3 (-) is a parameter employed to estimate mesh quality. A value of 1 would have meant a perfectly regular mesh and a value of 0 would have implied the presence of degeneration in any of the directions. All our meshes had a value of 1. It should be kept in mind that the applied numerical method assumed that cells were relatively equilateral; that is, with a value of the determinant 3x3x3 parameter close to 1.

2.3 Simulations

ANSYS Fluent® (ANSYS, Inc. Canonsburg, PA, USA) was used for all the simulations, which were run under Windows 7 on a computer with eight Intel (R) Xeon (R), 2.80 GHz processors and 16 Gb RAM. The RANS turbulence model was used, air was assumed to be an incompressible and isothermal fluid, with a Newtonian behaviour.

To simulate the flow near any surface (ground and canopy), Fluent® requires two parameters: roughness height k_s (m) and roughness constant C_s (-). To determine the value of k_s, it is necessary to define another parameter, the roughness length (z_0). Different authors propose tables with many values of z_0 as a function of surface type. Considering that there are no noticeable obstacles in the ground, z_0 = 0.001 m was used (Arya, 1988). A k_s = 0.019 m was obtained. Blocken *et al*. (2007) indicated that serious flow prediction errors may occur if k_s is above half the height of the nearest cell to the solid (y_p). As the minimum cell size was 0.04 m, we had a y_p = 0.02 m. The surface of the solid region representing the first canopy was considered very smooth ($k_s = 0$). No references were found for C_s, so the default value (0.5) was taken for both surfaces.

For the outlets, we considered a turbulence intensity I (%) = 5% and a turbulent viscosity ratio $\mu_t/\mu = 10$. These values are frequently used in environmental engineering to model atmospheric flows.

Fluent® uses Darcy's equation to estimate the pressure drop caused by the resistance of a porous body to the flow. This equation adds the estimation of losses due to inertia and to viscosity. Viscosity was considered to be negligible and an inertia value of 7 m^{-1} was assigned to the region corresponding to the canopies of the trees in the second and third rows, in accordance with previous results (Salcedo *et al.*, 2013).

The SIMPLE algorithm was used to solve the linear pressure-velocity coupling (Ferziger and Peric, 2001). The convergence criterion for simulations was to obtain a minimum normalised residual value of 10^{-4}.

2.3.1 Selection of cell size.

Three simulations having the above-described mesh resolutions were performed for each canopy geometry. In these simulations, a constant air velocity of 10 m/s normal to A and B air inlet areas of the domain was simulated. Airflow turbulence was characterized by the parameters turbulence intensity I (%), defined in equation (1), and characteristic length L (m). I was considered to be 10% in all the air inlet sections (default value in Fluent). L is the theoretical size of any vortex in a specific section. Initially, Fluent proposes a value of 1 m, but this is bigger than the height of each air inlet section. A value of 5% of the height was employed, following the suggestion of Delele *et al.* (2005) for studies with airblast sprayers.

In all these simulations, the standard k-ε turbulence model was employed, with a first-order scheme.

The objective variables of the simulations were the velocity magnitudes at the points equivalent to those of post D in the trial. The difference between mean velocity magnitudes of two consecutive meshes for each geometry was calculated. If the value was lower or equal to 0.1 m/s, the biggest size of cells was chosen, otherwise the smallest.

2.3.2 Selection of the geometry at the first canopy and the turbulence model.

Turbulence model choice substantially affects simulation accuracy (Franke *et al*., 2007). For this reason, three models were compared: standard k-ε, Shear Stress Transport (SST) k-ω and Reynolds Stress Model (RSM).

Twelve simulations were run combining the three turbulence models and the four canopy geometries. In these simulations, a numerical second-order scheme was followed. In order to reduce computational effort, first simulations with standard k-ε model were run. When these converged, simulations with the SST k-ω model were performed using previous simulation results as initial solutions. Finally, the RSM models were generated in the same way. All the simulations converged in a second-order method.

In all these simulations, the velocities and turbulence intensities recorded on posts A and B in the trial were employed as boundary conditions. *L* was 5% of the air inlet length as in the previous simulations.

The objective variables of the simulations were the velocities at all the measuring points in the trial (except A and B, which correspond to the air inlet area in the model).

In order to assess the goodness of fit of the models, first it was checked if they reproduced the main flow structures observed in the field experiment (Figure 6) (Salcedo *et al*., 2013, 2015): a vortex behind the first tree and another over its canopy, together with a strong airflow under the canopy. For this purpose, the velocity vectors observed at each trial point were graphically represented together with those obtained in the simulations. Besides, angles between real and simulated vectors and the magnitudes of the difference vectors were calculated.

Because the main objective for the model was to reflect general flow performance, more importance was given to the direction of air vectors than to the value of their magnitudes. For this reason, the models that fulfilled the following requirements were preselected:

- Post C should represent the fan velocity profile as much as possible. However, differences between simulated and observed data were expected, due to the turbulent nature of the flow and to the inaccuracy of the measurements. For this reason, we considered only as valid those models whose maximum mean variation between experimental and simulated magnitudes of velocities were lower than 20%. At the same time, the maximum allowed average angle between experimental and simulated velocity vectors was 20º. These threshold values were set arbitrarily.

- Post D should reflect the first vortex behind the tree, and from 2.6 m, the presence of the second vortex. In each point of the simulation where the vortex was reproduced, the magnitude of the velocity had to be of the same order of magnitude as the corresponding experimental point.
- Posts E, F and G should reflect the vortex above the canopy. In each point of the simulation where the vortex was reproduced, the magnitude of the velocity had to be of the same order of magnitude as the corresponding experimental point.

From the preselected models, the final one was that with the lowest differences between experimental and simulated data.

2.4 Model validation with experimental data from a second trial

Model validation consisted in comparing the simulation results of the selected model with the data obtained in a second trial realized by Salcedo *et al*. (2013, 2015). In this trial six posts in vertical positions (A*, C*, D*, E*, F*, G*) and one in horizontal position (B*) were employed (Figure 7). Post A* was 4.5 m high. Posts C* and D* were placed between the fan and the trunk tree, and measurements were taken every 0.5 m up to 4.5 m. Posts E*, F* and G* stood behind the canopy and air velocity was measured every 0.3 m up to 3 m and then every 0.5 m up to 4.5 m. The posts were aligned with the centre of the fan outlet and the trunk. During this trial, weather conditions were measured in the same way as the previous field experiment and were: average air temperature 26.3 ºC; average relative humidity 67.9%; average wind speed 1.0 m/s (all the values were below 1.5 m/s); average wind direction 211.1º (from West-South) respect to the tree row (North-South).

The air inlet boundary conditions were the air velocities and the turbulence intensities set at the measurement points of posts A* (from 0.4 to 1.8 m high) and B* of this experiment. The objective variables were the air velocities and directions at the points on post A* from a height of 2.0 m, and at the points on posts C*, D*, E*, F* and G*. Data analysis was performed following the methodology described in section 2.1.2. Measurement points that were not stable were not included in the subsequent comparisons.

The simulation was considered valid if it represented the global flow (correct air inlet and vortices around the first tree). The following criteria were considered for this purpose:

- At the measurement points in front of the canopy:
    - On posts A*, C* and D*, it was checked that the simulations reflected the air current around the tree and that the order of magnitude of the simulated air velocities where similar to those observed in the experiment.
- At the points behind the tree (which corresponded to posts E*, F* and G*), the following were considered:
    - For post E*, the same criterion that was used for selecting the first canopy geometry was considered.
    - On posts F* and G*, it was checked that the simulations reflected the flow structures behind the tree and that the order of magnitude of the simulated air velocities where similar to those observed in the

experiment. Low air velocities measured on posts F* and G* (0.2-0.7 m/s) indicated that these regions were less influenced by the strong airflow generated by the fan making them more susceptible to the effect of other factors not included in our study (morphology of the terrain, influence of 3D turbulences not included in a 2D model, etc.).

3. Results and discussion

3.1 First trial to adjust the model

3.1.1 Air velocity measurements and turbulence intensity estimation for boundary conditions

The measured air corresponding to the measuring points on posts A and B are shown in Figure 8. The horizontal component U_y could be seen as dominant over the first 1.8 m of post A. The vertical component U_z became increasingly higher at the top of this post. The airflow began moving towards the ground, but then rose. At post B, the vertical component became larger as we approached the centre of the fan, as it happened in other experiments (Salcedo et al., 2013, 2015).

Turbulence intensities on post A ranged between 5% and 15%, except at a height of 0.4 m (Figure 9i). This was because the magnitude of the air velocity was much lower at this point (Figure 8) which makes it more prone to fluctuations. The intensities on post B were larger (10%-30%) (Figure 9 ii) and decreased as they approached post A.

Although the data acquisition rate of the anemometers (1 Hz) may not very high to calculate the intensity with high accuracy, we considered that this was a better approach than that followed by Endalew *et al*. (2010b), who used a constant value that was not obtained in their experiments, or that followed by Da Silva *et al.* (2006), who omitted these data.

3.1.2 Air velocities measurements to select the model

Vector diagram of measured velocities at the different points is shown in Figure 10. At the points corresponding to post C, the airflow was quite horizontal up to a height of 2.0 m, and maximum values (21-23.0 m/s) were obtained at a height of between 0.4 m and 1.0 m. The horizontal component of the air velocity vector, U_y, pointed always at the first tree. The vertical component, U_z, pointed at the ground for the first 0.6 m, but then changed to an upward direction. At a height of 2.0 m, both components had similar values. Up to 3.0 m, air velocity became slower and more vertical because of the effect of the canopy, which made the air to move upwards.

Behind the tree (points on post D), the direction of the velocity vectors changed from the bottom to the top. This can be caused by an anticlockwise vortex. All the vertical components pointed downwards to the ground and horizontal components U_y were generally larger. Vectors pointed the next tree up to a height of 1.2 m, as a consequence of the strong air stream passing below the canopy. However at a height over 1.4 m, the direction of the horizontal component reversed. This suggests that a clockwise vortex was generated over the canopy.

The air velocities at the points over the canopy reflect how air kept recirculating over the canopy. Both components had a negative sign at the points corresponding to the post in position F (centre of the tree) and in position G. This confirms that the airflow over the canopy probably formed a clockwise vortex, although our experimental data were only able to show the lower part of it.

All the velocity data at all the points met the proposed equilibrium criterion. Therefore, they were considered adequate to be compared with the results of the simulation.

3.2 Selection of cell size

Table 2 presents the mean differences of the results between two meshes of consecutive sizes. In all cases the differences between the results obtained with the mesh with cells whose side measured 10 cm and with that measuring 4 cm still increased by more than 0.10 m/s. Therefore, the 4 cm side cell size was used in all the remaining models.

3.3 Selection of the canopy geometry and the turbulence model.

Figure 11 shows the airflow generated by all the geometries for the k-ε standard model, as example to explain the results in each one. It also shows the airflow generated by the Geometry 2 for the other turbulence models considered.

The Geometries 3 and 4 for the canopies (Figure 11iii, iv) did not meet the expected goodness requirements when using any of the tested turbulence models: a) the mean variations between experimental and simulated velocities magnitude were over 20%, b) no vortex was generated at points corresponding to posts E, F and G, and c) there were two vortexes behind the tree between 1.0-2.0 m high. For Geometry 3, the mean angle formed by the actual vector velocities and the simulated ones among all the posts was 78.4º and the variation between magnitudes was 26%. These values were respectively 76.3º and 25% for Geometry 4. For both geometries, the highest differences between the measured and simulated air velocity values were located on the points corresponding to the posts situated over the canopy.

In both geometries, with this turbulence model and the others, two vortices were observed, although the vortex over the canopy of the first tree was displaced to the right and is smaller than expected. This, in turn, affected the vortex behind the first tree, which was simulated with lower velocities than the ones measured on post D. As a consequence, these two geometries represented the airflow which passed over the tree more horizontally than it really was.

Simulations with Geometry 1 (Figure 11i) met the established criteria both in front of and behind the tree canopy. However, irrespectively of the turbulence model used, they did not reproduce adequately the vortex over the canopy. In front of the tree, the mean angle between the simulated and measured velocity vectors was 16.8º and the mean variation of the magnitudes of the vectors was 22%. Once again, the highest differences were observed at the points over the tree.

Figure 11i shows how the vortex over the canopy was still not present in the area covered by posts E, F and G. This vortex was more intense than with Geometries 3 and 4, but only was situated further away from the tree. This indicated that the simulated airflow over the tree was still more horizontal than the observed in the field.

Geometry 2 was the only that met the selection criteria, except when working with the k-ε model (Figure 11ii), as it will be explained later. The simulated air stream over the canopy separated earlier than in the other geometries (Figure 11v, 11vii), so it became more vertical. This implied that the vortex simulated over the canopy was stronger and closer to the canopy (simulated velocities were closer to actual velocities measured on post G).

Table 3 summarises the results obtained for Geometry 2 using the different turbulence models tested. The standard *k-ε* model was discarded because did not reproduce the vortex over the canopy in posts E, F and G. Considering the other two models, SST *k-ω* fitted the flow structures better than RSM (Figure 11v,vi). The latter reproduced the vortex above the canopy and situated it above the centre of the canopy. Furthermore, the differences in the angle between vectors and in the magnitudes variation were smaller, thus representing a model closer to the experimental data. The mean angle between the real and simulated vectors for the SST *k-ω* flow turbulence model was 10º and the mean variation between magnitudes was 16%, with the highest differences at points situated on post E.

Figure 10 depicts both the experimental and simulated vectors for Geometry 2 and the SST *k-ω* model. Both velocities had similar values and directions at points on posts C and D. The angles between them grew with increasing height in front of the tree, but never exceeded 10º. Simulated air velocity magnitudes on post E increased and exceeded the experimental values. The simulated velocities at the two lowest points of post G and the lowest point of F had a negative horizontal direction and approximately the same magnitude as the experimental did, indicating the presence of a vortex. However, this simulated vortex was in a lower position than the one indicated by the experimental data. Besides, this vortex was slightly displaced to the right of the figure, because simulated and actual velocities have opposite directions in the upper points of post F.

3.4 Model validation with experimental data from a second trial

In general the model simulated properly the airflow before the tree although with a more marked presence of a vertical component than in the experimental data (points of posts A*, C* and D*) (Figure 12). The highest differences between simulated and experimental data were found on post A*, meanwhile, the model was better fit at posts C* and D*. In post A* the angles between the experimental and simulated velocities vectors grew with height, and from 2.5 m the experimental velocities returned to the fan. Nevertheless, in C* and D* the simulated current behaved as in the field test, and it went over the tree into the atmosphere.

On the other side of the tree, on post E*, magnitude and direction of the simulated and actual velocities were similar in all points. On posts F* and G*, simulated velocity directions below 1.5 m are similar than those in the experiment, although magnitudes are larger. Above 1.5 m they have opposite directions but are less than 1 m/s in almost all cases. However, we can consider that the model reproduced the two vortices found in the field test, one over the canopy and the other behind the tree. The upper points of post E* (from 3.0 m to 4.0 m) indicated the vortex over the tree, because horizontal directions were negative and the current pointed downwards. The vortex behind the tree was simulated by the changes of direction of the velocities at points below 1.5 m on posts E*, F* and G* (Figure 12).

The model was able to reproduce the same turbulent structures in the same order of magnitude as in the trial. However, the experimental velocities in front of the tree were less intense than in the model. This indicates that although the model can reproduce the general behaviour of the phenomenon, it overestimates the air current in front of the tree. This may happen because we worked in two dimensions. Probably in a 3D model, the dissipation will be higher and the velocities will be adjusted better. There will be more space to displace around the tree and the air will not focus on the same area.

4. Conclusions

This work proposed a method to model the airflow produced by an airblast sprayer in front of a citrus canopy. The first step was to work in two dimensions to define the characteristics and the turbulence air model. The simulations reproduced the vortices deducted from experimental data: one over the canopy and another behind the canopy.

This work has also highlighted the importance of collecting experimental data not only in front of and behind the tree, as it is often the case, but also in other areas, like above the canopy, which may have an important influence on spray drift.

Moreover, this manuscript emphasizes the importance of using turbulence models other than the standard *k*-*ε* (the most widely used in similar works). This model was unable to reproduce the vortex behind the canopy. The SST *k*-*ω* model fitted the experimental data better than the RSM.

Another aspect to bear in mind is the importance of the shape when representing the canopy as a solid region, since it strongly influences not only the flow near the canopy, but also in front of the air inlet of the model. The simulations showed that this geometry can generate a large vertical component to the airflow in front of the tree and varies the position of the vortex above the canopy.

Despite using a 2D model for describing the airflow generated by the fan of an airblast sprayer, which is very turbulent and heterogeneous, it was possible to adequately reproduce the airflow vortices without high computational costs. However, 3D simulations are required to avoid overestimations in air velocities and for a better understanding of the airflow. The characteristics defined in this work (solid body for the first canopy an SST model) could be used to design a 3D model. Future approaches could be focused on the step from stationary to dynamic (driving) situation of the sprayer, single and multiple row situations, and the base effect of ambient wind speed and direction.

5. Acknowledgements

This work was partially financed by the Spanish Ministry of Economy (projects AGL2007-66093-C04-01 and AGL2010-22304-C04-01) and the European Regional Development Fund (ERDF). Ramon Salcedo is recipient of a postgraduate FPI-INIA scholarship. Authors would like to thank to Grupo Martinavarro S.L. for allowing the use of their fields and Pulverizadores Fede S.A. for the use of its sprayer.

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